*T. Albiol (IRSN) - L. Herranz (CIEMAT) - E. Riera (CSIC) - C. Dalibart (EDF) -
T. Lind (PSI) - A. Del Corno (RSE) - T. Kärkelä (VTT) - N. Losch (AREVA GmbH) -
B. Azambre (UniLor) – C. Mun (IRSN) – L. Cantrel (IRSN)*

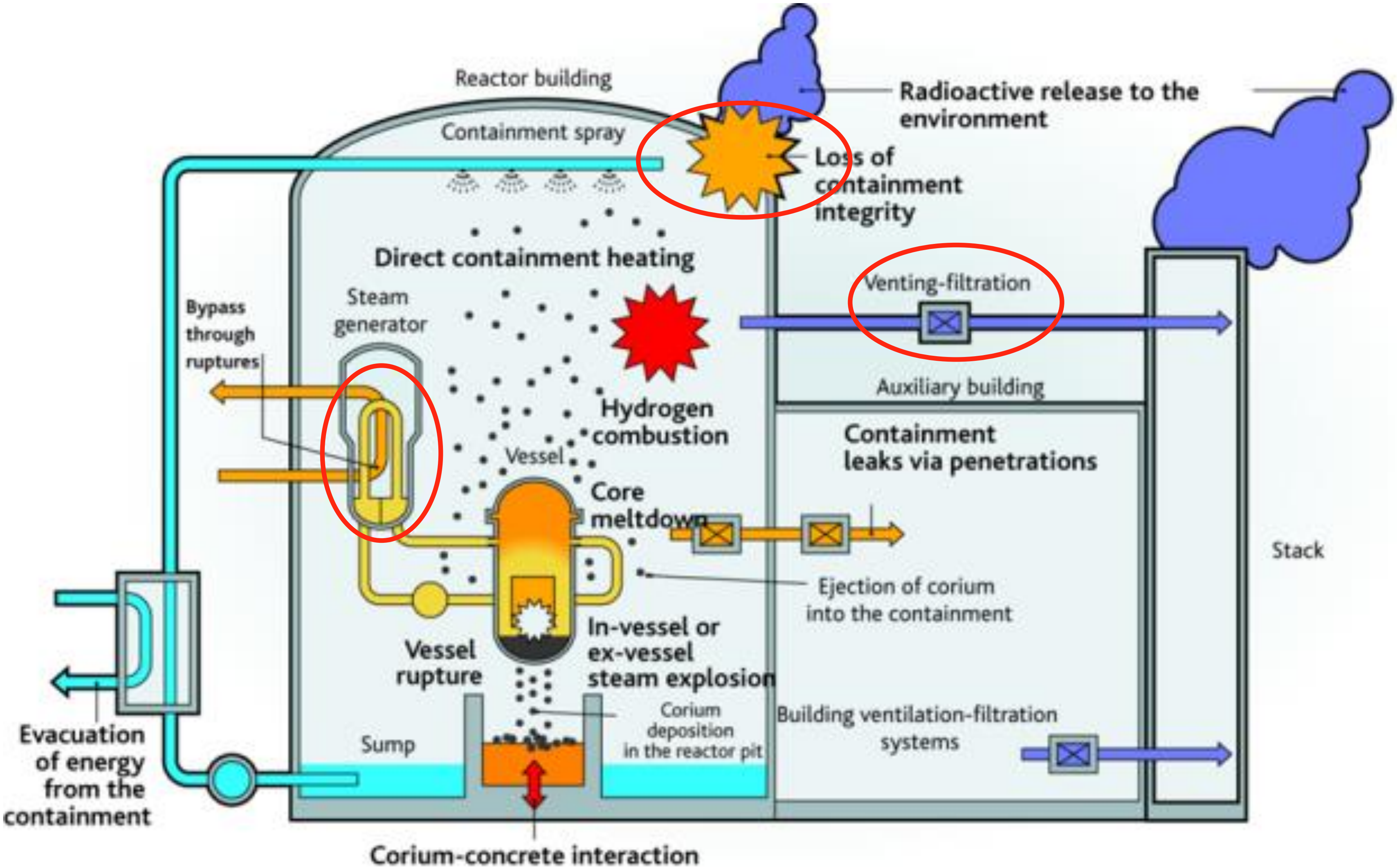
The European PASSAM Project – Main outcomes for enhancing severe accident source term mitigation

EUROSAFE 2017

*This presentation is just to give a general overview of the main outcomes of the European PASSAM project… Due to the rather large scope of the project, the presentation cannot give much details but it illustrates **some selected results**. Refer to specific articles or papers in various conferences and journals for more details.*

Content

- PASSAM context, objectives and main features
- PASSAM experimental studies and focus on some selected major results
- Conclusions


Reactor building
Containment spray
Radioactive release to the environment
Loss of containment integrity
Direct containment heating
Venting-filtration
Steam generator
Bypass through ruptures
Hydrogen combustion
Auxiliary building
Vessel
Containment leaks via penetrations
Core meltdown
Stack
Ejection of corium into the containment
In-vessel or ex-vessel steam explosion
Vessel rupture
Corium deposition in the reactor pit
Building ventilation-filtration systems
Sump
Evacuation of energy from the containment
Corium-concrete interaction

PASSAM context: severe accident source term mitigation

- After the **TEPCO Fukushima accident of March 2011**, one of the main concerns of the nuclear industry has been the search for improved atmospheric source term mitigation systems.
- Several countries (Sweden, Switzerland, Finland, Germany, France, in the early 1990's, then later on, the Netherlands, China and Bulgaria) had already implemented **Filtered Containment Venting Systems (FCVS)** before the Fukushima accident. Many other countries have considered (and several of them decided) the implementation of FCVS more recently, in the post-Fukushima context.

↓

- New national R&D programmes and new **coordinated international activities** on FCVS.

↓

- Call for offers launched by the **European Commission** in 2012.

↓

- PASSAM: "Passive and Active Systems on Severe Accident source term Mitigation".

PASSAM objectives

- PASSAM is an R&D project of experimental nature, mainly on FCVS, aiming at:
  - Exploring potential enhancement of existing source term mitigation devices: aqueous ponds; sand bed filters (+ metallic pre-filters).
  - Demonstrating the ability of innovative systems to achieve larger source term attenuation: preconditioning stage (acoustic agglomerators; high pressure sprays); filtering stage (electrostatic filters; improved zeolites; dry & wet combined filters).

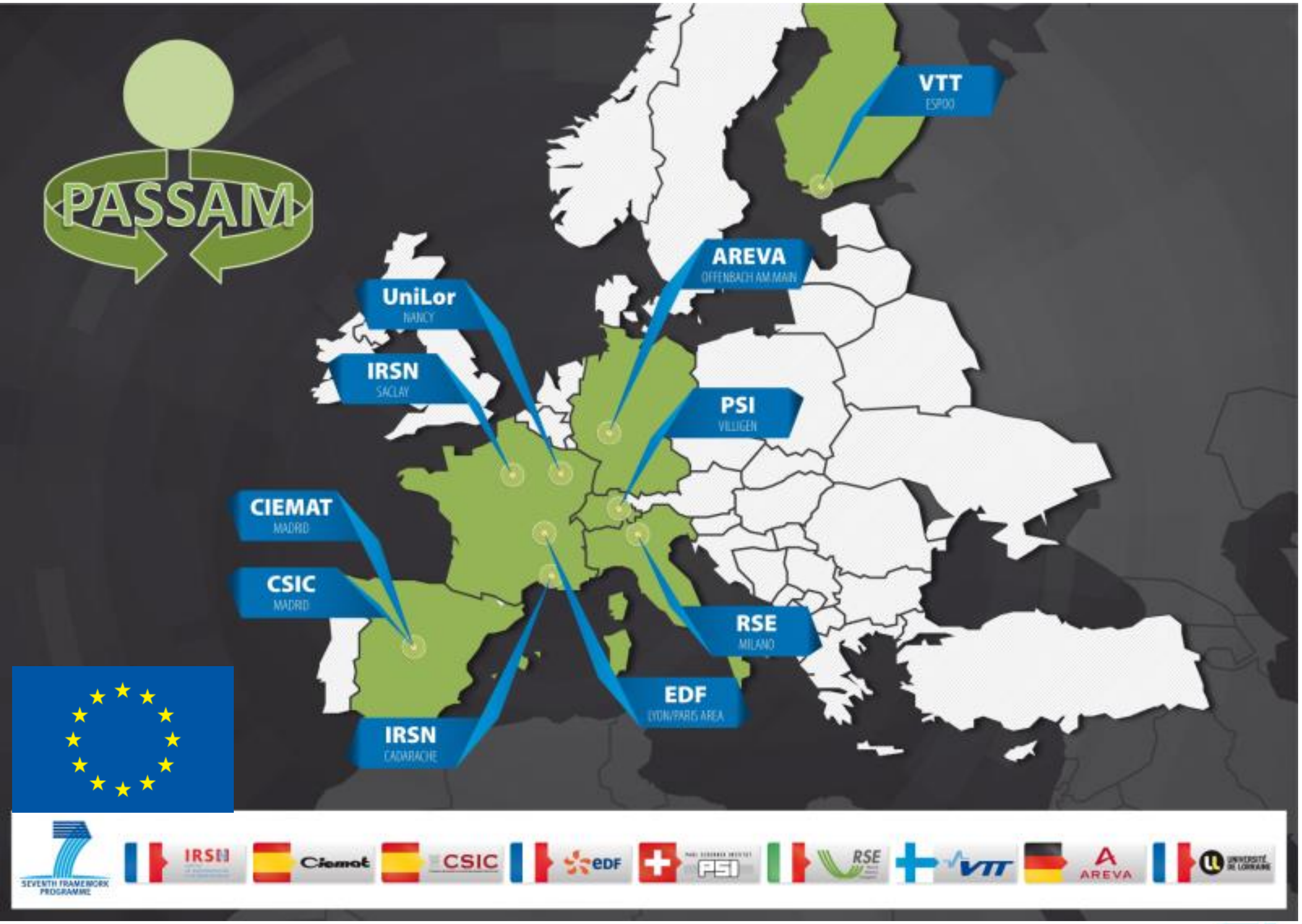
- The understanding of physico-chemical phenomena gained from in-depth analysis of experimental results made possible to produce simple models and/or correlations easy to be implemented in accident analysis codes. Then, the use of these codes will allow enhancing the capability of modelling Severe Accident Management scenarios and developing improved guidelines.

- The project’s outcomes constitute a valuable database which may be strategic for helping the utilities and regulators in assessing the performance of the existing source term mitigation systems, evaluating potential improvements of the systems and developing severe accident management measures.

PASSAM main features

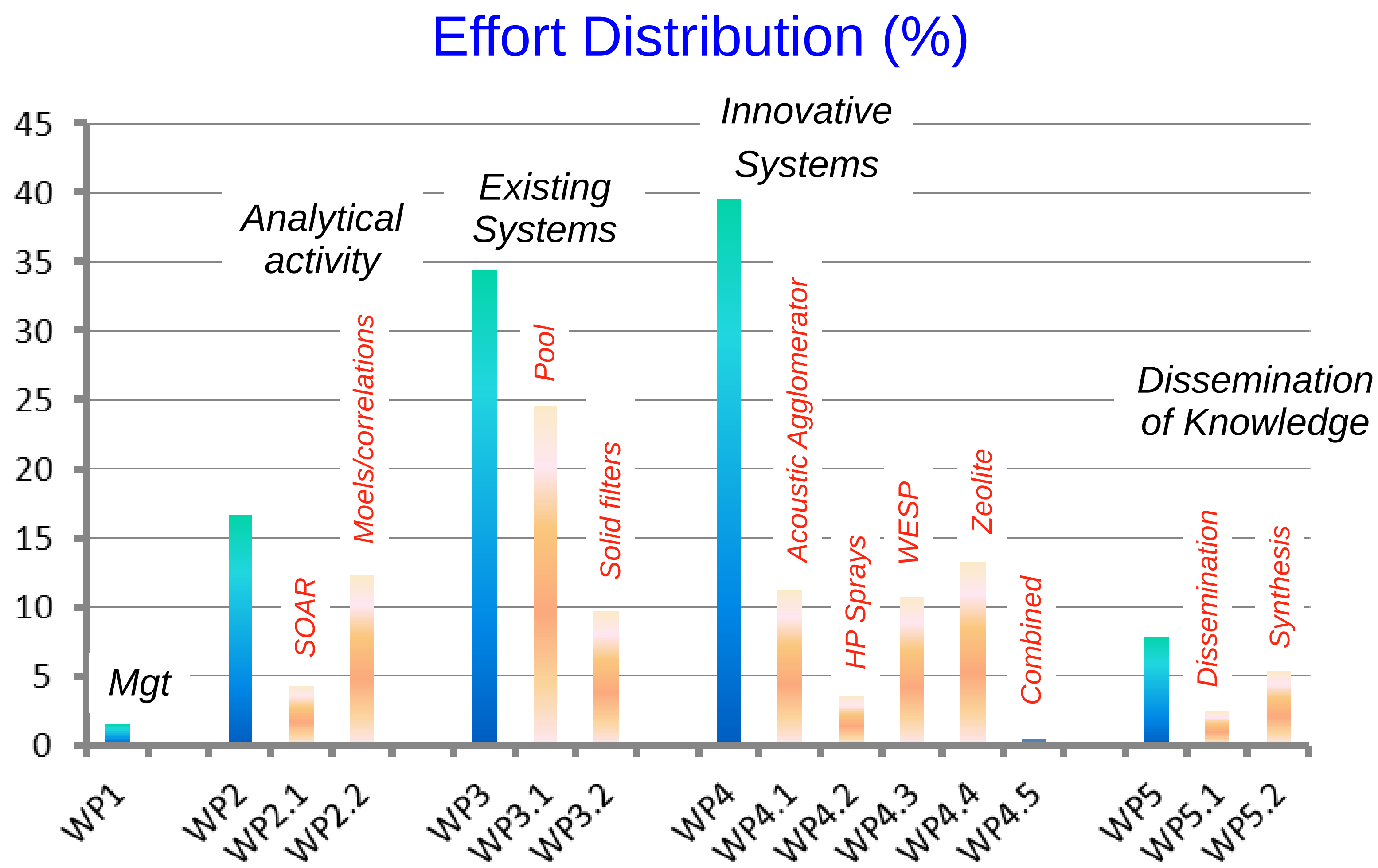
- Four years duration: 2013 – 2016.
- Partnership: 9 partners, IRSN (France) Coordinator.
- Large amount of work : 395 person.months (33 person.years) for the 9 partners.
- Total budget: 5.11 millions euros, out of which 71% are funded by the European Commission.

Initial figures. Finally, significantly more.



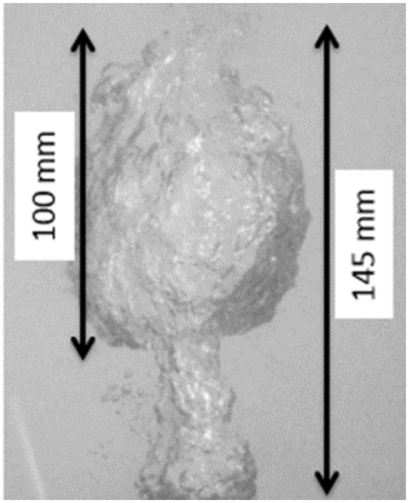
PASSAM project partnership

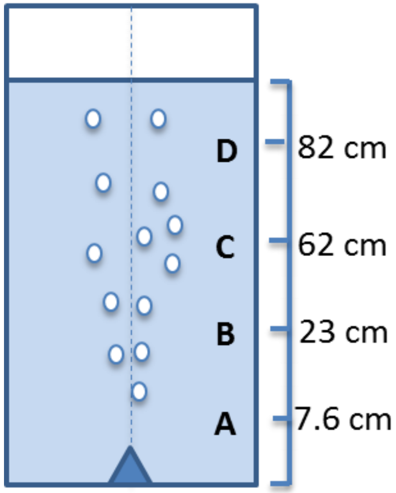
PASSAM organization: 5 work packages



PASSAM: pool scrubbing under jet injection regime (CIEMAT, Spain)

- ***Objectives***
  - To build-up a “scaled” data base on “jet scrubbing”.
- ***Major outcomes***
  - Jet injection occurred in a pulsated way (frequency dependent on $\dot{m}_{gas}$).
  - Unsteady jet trajectory (oscillatory position of “jet plume”).
  - Transition from jet to bubble swarm started! (in 0.3 m water depth).
  - Extremely rough and wavy water surface.
  - Aerosol retention efficiencies ranging from 82,8 to 97,5 % in all the tests (except one).
  - Confirmation that once jet regime is well developed (We>10^6), inertial mechanisms between particles and droplets are responsible for scrubbing.
  - A good approximation through an empirical approach might be achieved by proposing expressions based on a reduced number of non-dimensional magnitudes.

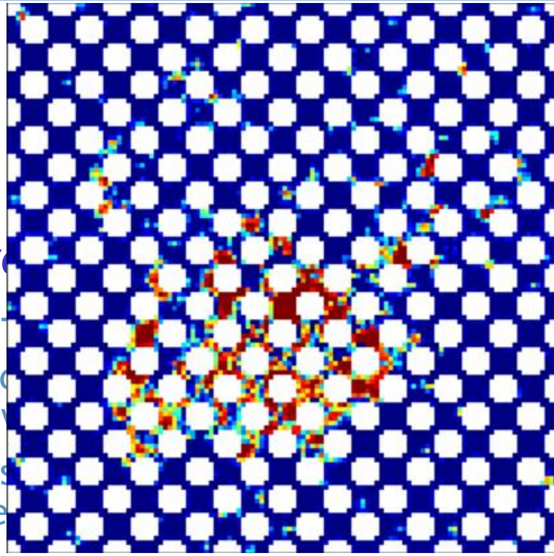


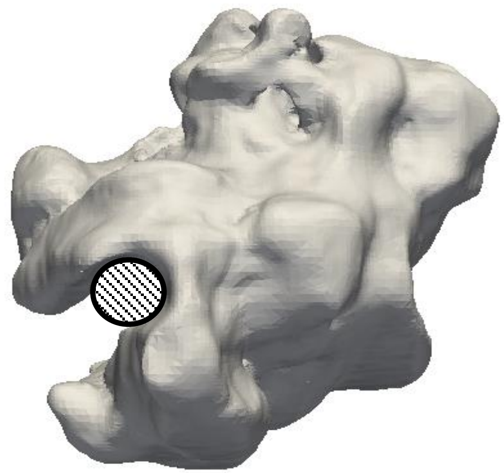


- ***Objectives***
  - Tests in the RSE SCRUPOS facility aimed at bubble studies and at aerosol retention in natural water, sea water and in the presence of additives. Three measurement technics: optical probe, photo camera and video camera.

- ***Major outcomes***
  - Data both on bubble hydrodynamics and aerosol retention confirmed how in the jet zone a three phase liquid-gas-droplet model is required while in the rising zone, taking into account two-phase gas-liquid interactions is enough to well estimate the retention efficiency.
  - The rising velocity of bubble swarms was confirmed as a key parameter that should be upgraded.
  - Higher decontamination was measured in sea water and water with surfactant than in demineralized water mainly due to an increase of contact surface between the liquid and the gas phase.
  - Models could be obtained, which should be applicable to S.A. codes.

PASSAM: Two-Phase Flow Characteristics under SGTR Conditions (PSI, Switzerland)

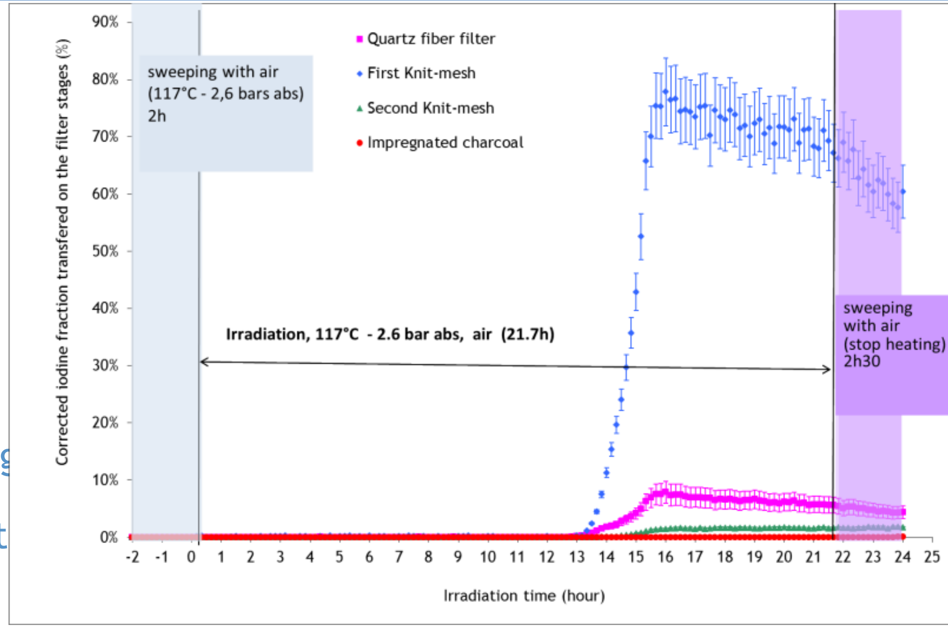




- ***Objectiv***
  - SGTR - … oact
  - Hydro… pe bu … unkno… stan
  - Models … code … efficie

- ***Major outcomes***
  - Void fraction, detailed bubble shapes and size distributions, gas phase velocity as well as interfacial area concentration were determined based on the wire-mesh sensor data and high speed camera. Experimental data allows more credible estimates of the multiphase phenomena than existing models in low injection regimes.
  - Valuable insights on the dominating fluid flow regimes: clear differences were observed between different flow regimes and channel geometries.
  - The role of submerged surfaces (e.g. tube bundle in the secondary side of a steam generator, in case of a SGTR accident with this secondary side still is flooded) was clearly evidenced.
  - Good understanding of bubble sizes and bubble spreading in a bare pool and in a SG geometry → Real improvement of the knowledge for understanding DFs in pool scrubbing. Models derived from experiments allow to get a more realistic gas phase velocity (much larger) and bubble size (existence of large bubbles) for the SGTR and bare pool at high injection velocities.

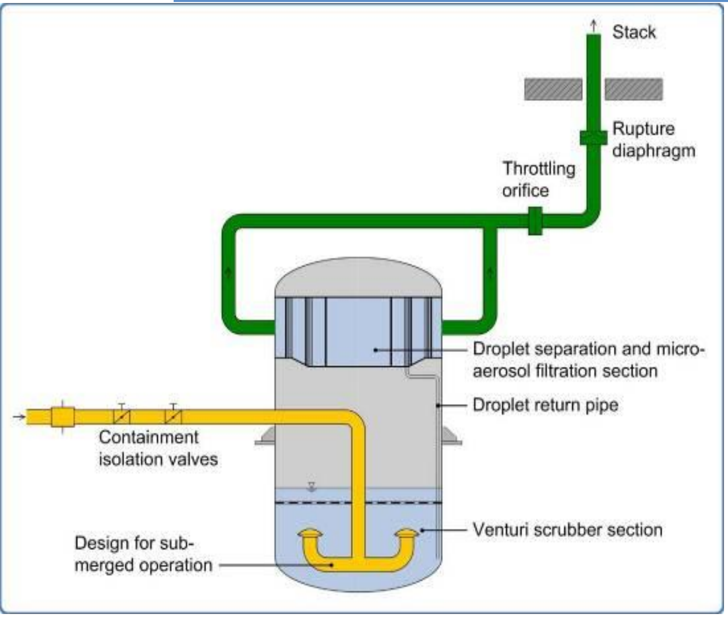
PASSAM: Long Term Behaviour of Iodine in Water Pools under Irradiation (IRSN, France)

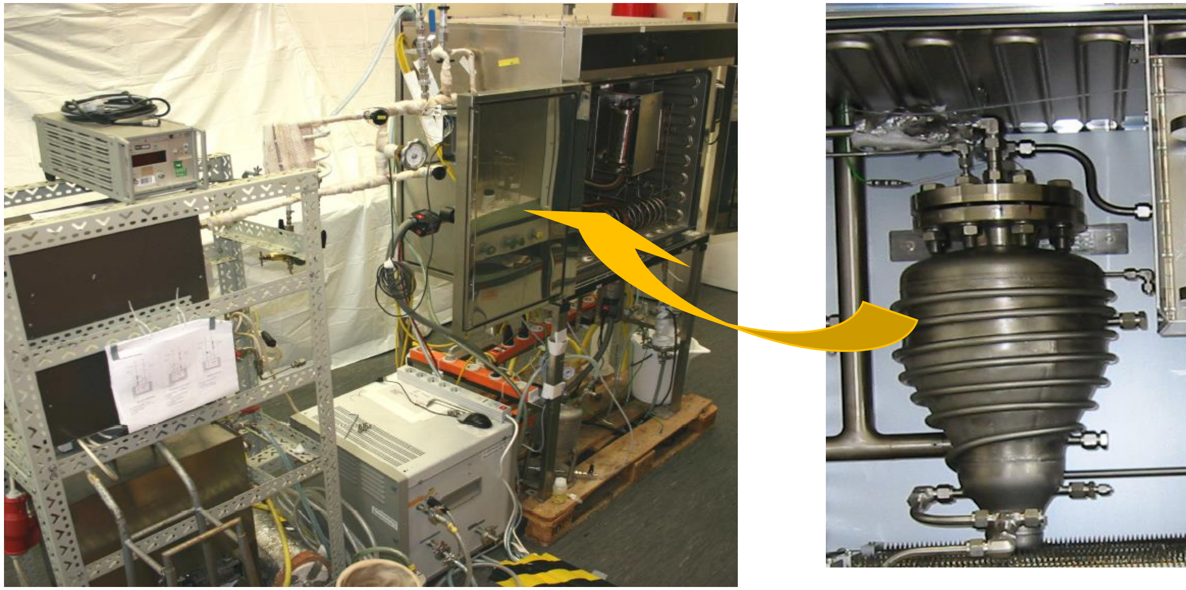


- ## *Objectives*
  - Experimental investig
    iodine compounds in
    conditions (temperat

- ## *Major outcomes*
  - When the water pool, initially alkaline, is unbuffered, radiation induces a strong pH decrease and iodine is released to the gas phase, essentially in inorganic form (mainly I_2).
  - When the water pool is buffered (pH maintained over 9.5), no direct release is measured but the iodine mass balance is low (67.9 % and 49.6 %) → mechanical entrainment of water droplets from the pool and/or evaporation of volatile species not trapped by the Maypack filtration system (HOI formation is strongly suspected).
  - The analysis (modelling) of the tests in alkaline conditions, coupled to the analysis of other tests (out of the PASSAM scope) allowed to conclude on a possible high contribution of the HOI species to the global iodine release from the solution… Although HOI could not be measured in the tests.
  - So, keeping an alkaline pH in the scrubber solution is absolutely necessary in order to avoid large delayed iodine release. Even with alkaline pH, the performance of pool-scrubber type FCVS might be limited by possible HOI volatilization phenomenon. In order to avoid an under-estimation of the Source Term in case of alkaline pH, it is proposed to implement in ASTEC V2.1 the models developed for HOI transfer and instantaneous conversion into molecular iodine (I_2) in the gaseous phase.

PASSAM: Retention of Organic Iodine in Water Pools (AREVA GmbH, Germany)





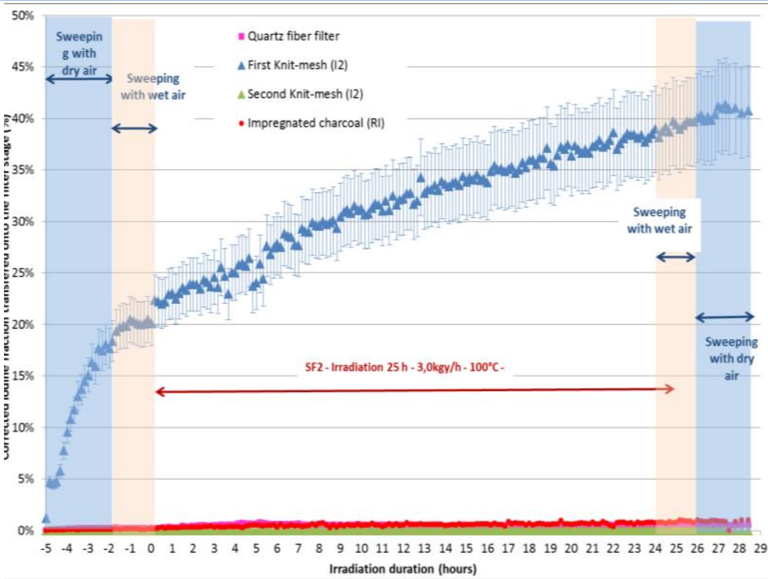
Objectives

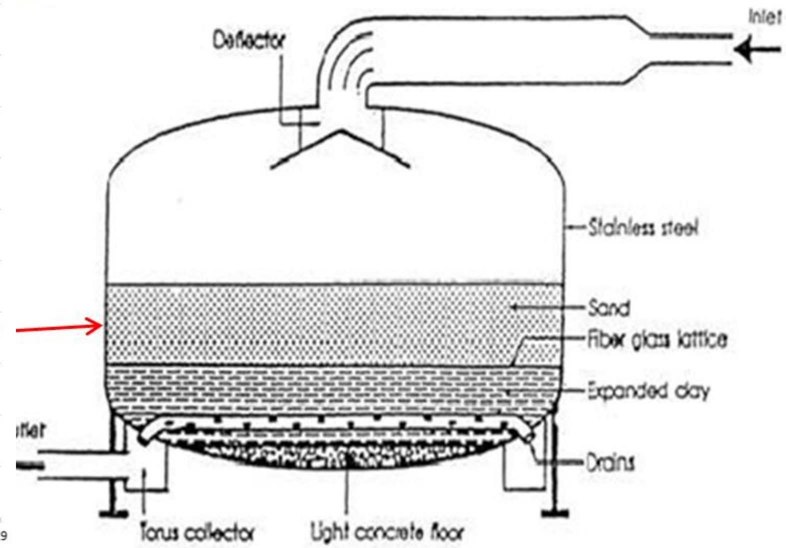
- Importance of organic iodine in the Severe Accident Source Term → Investigation of enhancement of existing pool scrubbing type FCVS for organic iodine retention

Major outcomes

- Laboratory screening tests regarding organic iodine retention of pool scrubbing systems were performed on the influence of scrubbing liquid composition (additives), of mixing elements and of temperature. The CH_3I retention in the scrubber could be moderately increased by Aliquat 336®, mixing elements, increased temperature… however, if Aliquat 336® scrubbing liquid is used, the retention performance is not further increased by mixing elements or by increased temperature (which even reduces CH_3I retention).
- Although direct scaling to the full scale FCVS is not possible, it is concluded that in any case the DFs are not high enough as regards new post-Fukushima requirements and that alternative filtration methods (e.g. dry filtration) are necessary to reach a qualitative step towards high CH_3I retention.

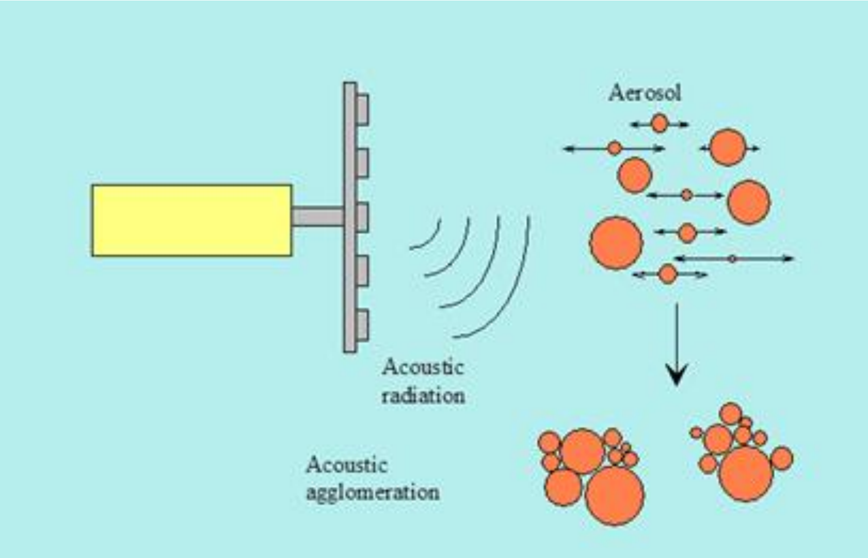
PASSAM: Behaviour of Iodine Trapped on Sand Bed Filters plus Metallic Pre-Filters (IRSN, France)

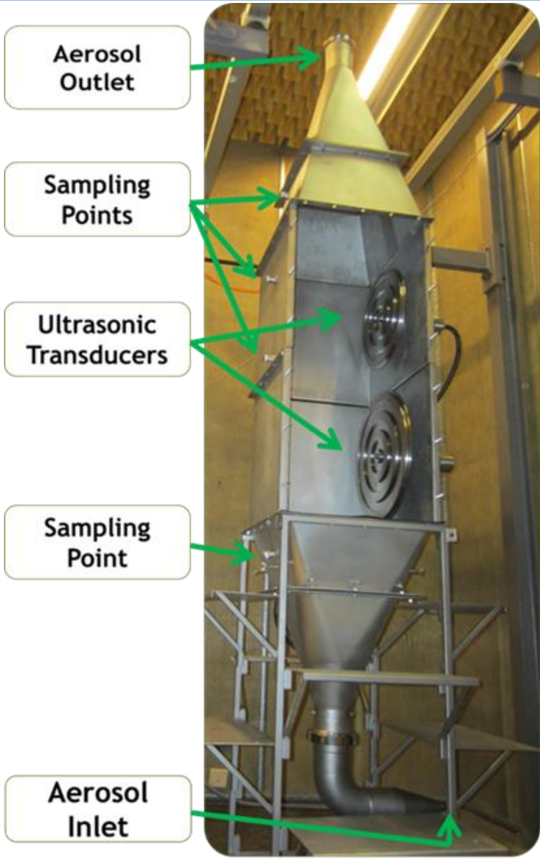




- ## *Objectives*
  - Sand bed filters plus metallic pre-filters were implemented on the French PWRs as FCVS in the early 90's for aerosol retention. Need to better investigate gaseous iodine retention and stability of trapped aerosols under irradiation.
- ## *Major outcomes*
  - Confirmation of non-trapping of organic iodides neither on sand filter nor on metallic filter and of significant trapping of molecular iodine on metallic filter.
  - CsI aerosols trapped on a sand bed filter are not stable under irradiation: a significant release of I_2 was observed (about half of the inventory in 24h). A model of CsI thermal-radiolytic decomposition was optimized: it is in good agreement with previous optimizations performed in the framework of the OECD-STEM project.
  - No gaseous iodine release under irradiation from CsI aerosols trapped on a metallic filter. Indeed, gaseous iodine might have been formed by CsI decomposition and then quickly trapped by the metallic filter.
  - CsI is the only aerosol species tested → What about other species (multi-component aerosols…)?

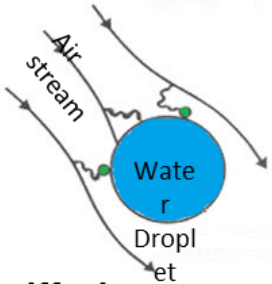
PASSAM: Feasibility of an Acoustic Particle Agglomeration System (CSIC and CIEMAT, SPAIN)



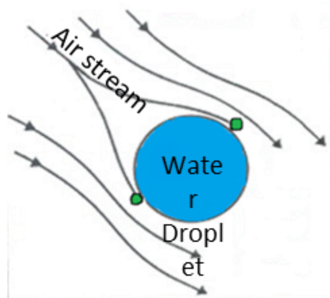


- ***Objectives***
  - Feasibility of an Acoustic Particle Agglomeration System to be mounted upstream of a FCVS in order to increase the particle size and so to enhance the global filtration efficiency of the system.
- ***Major outcomes***
  - Based on an agglomerator operating at 21 kHz, results confirmed that ultrasound agglomeration effect increases with particle number concentration and particle size dispersion and is proportional to acoustic intensity and treatment time.
  - A reduction of over 90 % of the aerosol particle number concentration was obtained in specific experimental conditions.
  - A numerical model was developed and experimentally validated.
  - From the model, the acoustic power required in case of a severe accident could be established (e.g. with aerosols of 0.5 microns, concentration of 0.1 g/m^3 and flow rate of 5 kg/s, about 240 kW are required for a particle number reduction of 90%).

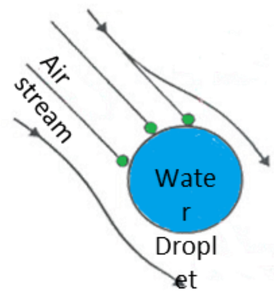
PASSAM: High Pressure Spray Agglomeration System (RSE, Italy)



Diffusion
(smallest particle)



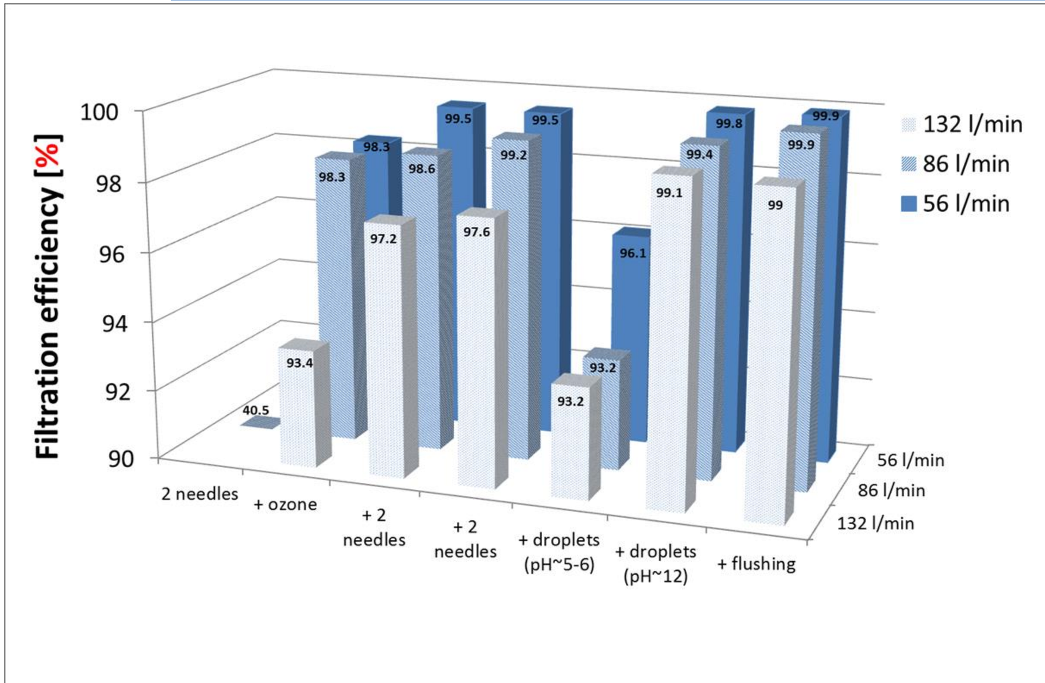
Interception

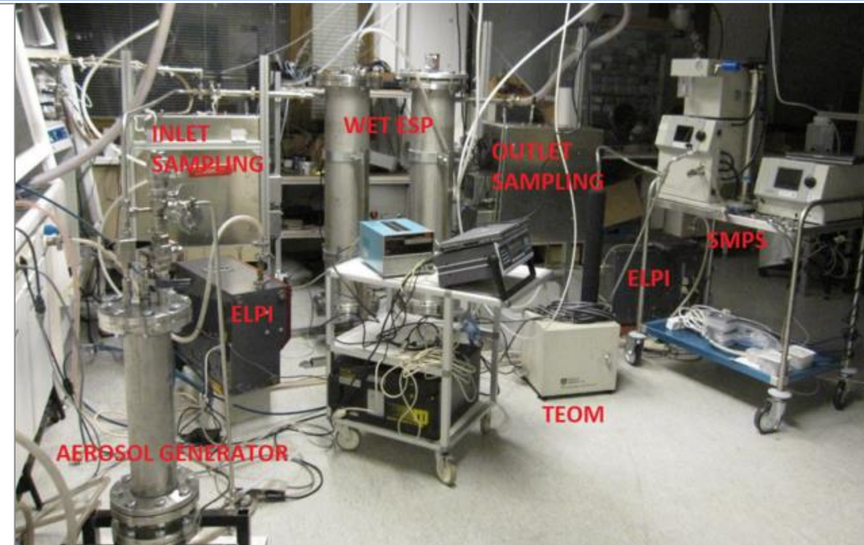


Impaction
(largest particle)

- ***Objectives***
  - Efficiency of a high pressure spray for decreasing the aerosol concentration and for agglomerating particles upstream of a FCVS in order to enhance the global filtration efficiency of the system.
- ***Major outcomes***
  - High pressure spray much more efficient than low pressure spray.
  - Aerosol removal rate increases with the particle size and spray pressure.
  - High pressure sprays can remove at least 99.9 % of particles of 1.5 µm AMMD in about one minute with a single-hole spray nozzle operating at 130 bar.
  - Modelling confirms that for aerosol smaller than 3 µm interception, and for aerosol smaller than 0.3 µm Brownian diffusion, are the main phenomena for aerosol capture even for small droplets .
  - Models have been established and successfully challenged to experimental results. Spray removal rate can be described by a single droplet capture efficiency involving mainly inertial impaction, interception and Brownian diffusion. This model was used to evaluate the retention in a three phase liquid-gas-droplet model for pool decontamination in jet regime.

PASSAM: Ozone Feed and Wet Electrostatic Precipitator Combination (VTT, Finland)

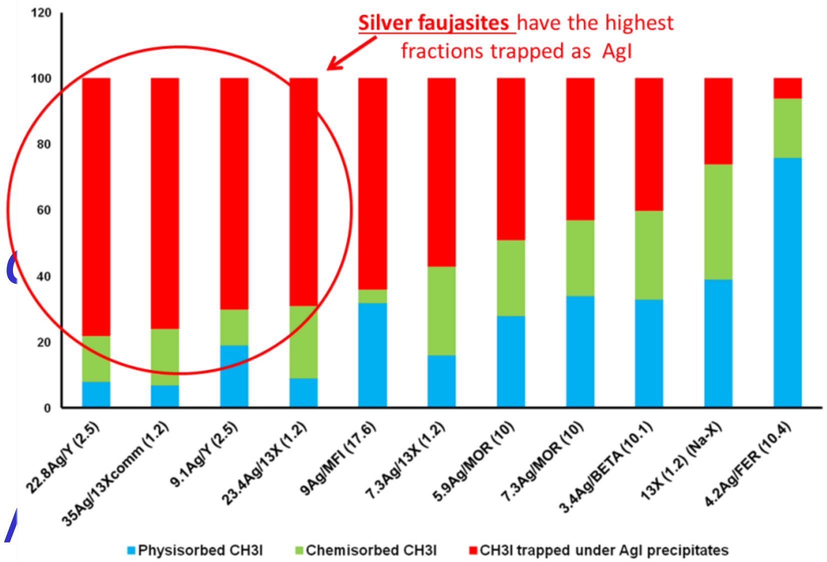


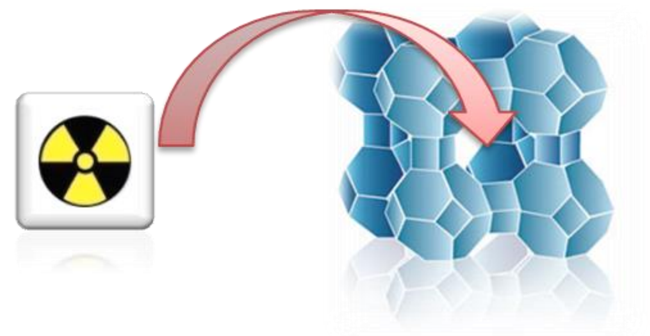


ı industrial filtration technic for removing
preseen conditions of a nuclear severe accident
pred, like radiation and high temperatures
(>90°C), and pressures (>1 bar); Filtration of iodine volatile species including organic iodides.

- ***Major outcomes***
  - One major innovative aspect consists of using an ozone generator upstream of the WESP, for transforming gaseous iodine species (I_2, CH_3I) into Iodine oxide particles.
  - Evolution of the iodine filtration efficiency according to the number of active corona needles, strength of electrical field, gas flow rate, use of droplets spraying and flushing walls with sodium hydroxide solution, nature and concentration of gaseous iodine and volume fraction of steam in the carrier gas was established.
  - In tested experimental conditions the retention efficiency varies from 97.6% to about 99,9% for I_2 ($42<DF<1000$), while the system is not really efficient for CH_3I.
  - Key phenomena which will have to be taken into account in scaling-up of the facility to real condition were determined in a model.

CH_3I Trapping stability (effect of zeolite type)

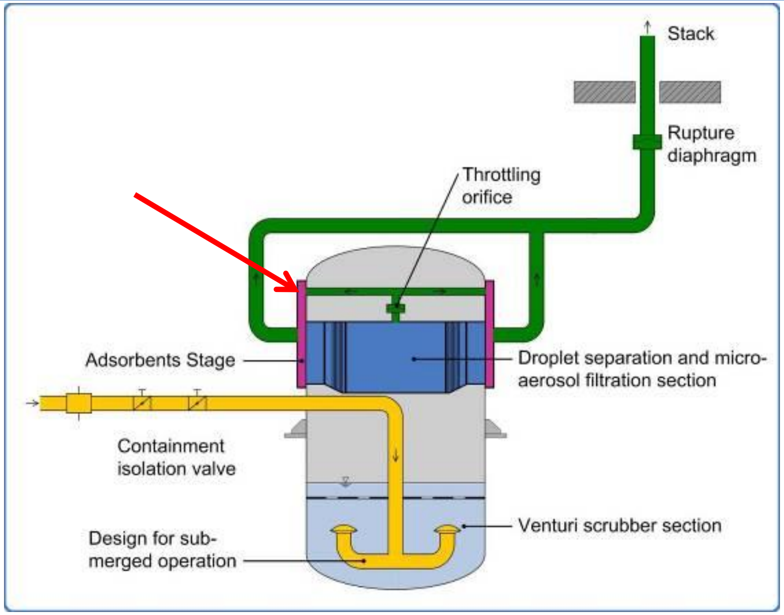




on zeolites (Microporous aluminosilicate crystalline
to dose rate), mainly for gaseous iodine retention: Effect
nvestigation of trapping mechanisms; extrapolation to

- Very large amount of data obtained, many parameters studied, significant improvement in the understanding of trapping phenomena of iodine by zeolites, good results in modelling.
- Optimization of zeolites for enhanced trapping of molecular and organic iodine in severe accident conditions. Faujasite Ag/Y and Ag/X sorbents with more than 15 wt% silver (and to a lesser extent Ag/MOR and Ag/ZSM-5) displayed the highest ability for irreversible iodine trapping.
- Trapping stability depends on the availability of silver sites to promote silver iodide formation. Very good stability of iodine trapped in silver zeolites under irradiation, no release observed.
- Increase of the silver content in silver-exchanged zeolites improves both the adsorption properties and trapping stability, but a silver content about 10 wt% may be enough for FCVS applications.
- The zeolite retention efficiency for iodine remained very good in conditions rather close from S.A. conditions and in presence of potential inhibitors, although complementary tests may be done on a wider range of conditions.
- Zeolite is one of the very few materials able to provide good retention for organic iodine. Furthermore, it is a passive system.

PASSAM: Combined Filtration System with third Retention Stage (AREVA GmbH, Germany)



- ***Objectives***
  - Develop an additional retention stage on a FCVS system to trap organic iodine
- ***Major outcomes***
  - Experimental investigation, using the large-scale JAVA test facility in representative S.A. conditions, focused on the organic iodine retention in the third, newly developed, additional retention stage of the AREVA FCVS PLUS design. Experimental parameters were: steam content, superheating, flow velocity, inlet pressure, pressure in the Molecular Sieve Section, and startup transient.
  - Experimental retention efficiencies over 98% for CH_3I.
  - Major parameters for CH_3I retention efficiency: superheating of the gas stream and residence time in the sorbent (zeolite) bed.
  - From test results, an appropriate design methodology based on empirical correlations was developed to adjust a customized design at industrial scale.
  - Zeolites are a passive system and superheating is got passively through a “sliding” process in the FCVS PLUS design.

PASSAM: Conclusions

- During four years (2013-2016), the PASSAM project involved 9 European partners bringing together their competencies and their various test facilities.
- The main technical outcomes were discussed in a final workshop of the project and are synthesized in the “PASSAM final synthesis report”:
  - Extension of the current database on the existing or innovative mitigation systems:
    - Gaseous iodine retention (molecular and organic iodine),
    - Hydrodynamics for scrubbers,
    - Long term stability of trapped compounds.
  - Deeper understanding of the phenomena underlying their performance.
  - Models/correlations easy to implement in accident analysis codes, like ASTEC.
  - Estimation of orders of magnitude for source term reduction for each filtration system, including on the long term, in accident conditions.

- PASSAM web site: https://gforge.irsn.fr/gf/project/passam/
- PASSAM final workshop: https://gforge.irsn.fr/gf/project/passam/docman/PUBLIC%20FILES/PASSAM%20Final%20Workshop%20Paris%20Feb%2028%20-%20Mar%201,%202017/
- PASSAM final synthesis report: https://gforge.irsn.fr/gf/download/docmanfileversion/10777/52721/PASSAM_DKS_T28_D5-5%20Final%20Synthesis%20Report.pdf

The authors thank the European Atomic Energy Community'(Euratom)
for showing a strong interest in the PASSAM Project,
and for funding it in the frame of the 7th framework programme FP7/2007-2013
under grant agreement n° 323217.

They also thank all the PASSAM contributors for performing all the experimental and modelling work.

And many thanks to all of you for your attention !!!